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We investigate the possibility of improving the W mass measurement at ATLAS. Given the high statistics of both W and Z bosons expected at the LHC, a sensitivity of $\sim$7 MeV per channel appears as a reasonable goal with 10 fb^{-1}.

1. Motivation

The Standard Model (SM) is a very predictive framework. Given precise measurements of α_{QED}, G_μ, and m_Z, the W boson mass plays a central role, as it allows for both a SM cross check, confronting predictions of the W and top quark masses [1] with measurements [2, 3], and limits on the SM Higgs boson mass [4]. Finally, constraints on the contributions of other heavy particles, like supersymmetric particles [5] can be obtained. The W mass precision has continually improved with statistics, yielding the current world average of $m_W = 80.398 \pm 0.025\,\mathrm{GeV}$ [6]. Further improvement will translate into more precise indirect predictions of the SM Higgs mass.

2. Event selection

The simulated W and Z boson signal and associated background samples used in this study are computed using the `PYTHIA` general purpose event generator [7], with photon radiation in W and Z decays treated via an interface to `PHOTOS` [8]. The size of the expected samples are computed from the NNLO W and Z cross-sections, as obtained from `FEWZ` [9], and simulated with complete simulation of the ATLAS detector using `GEANT4` [10].

At hadron colliders, W and Z events can be detected and reconstructed in the $e\nu_e$, $\mu\nu_\mu$, ee, and $\mu\mu$ final states. In the following, the term lepton (ℓ) will refer to either an electron or muon. Electrons are measured using the inner detector (ID) and electromagnetic calorimeter (EMC). They are reconstructed and identified with an efficiency of about 65%, while rejecting background from jets up to one part in 10^5. The transition region from barrel to endcap in the EMC ($1.3 < |\eta| < 1.6$) is not used. For muons, the ID is used together with the muon spectrometer with a reconstruction efficiency of about 95%. Backgrounds are less than for electrons, and diminished using isolation. The transverse momentum of the neutrino is inferred from the transverse energy imbalance as determined by the calorimeters. The relative energy resolution is typically 1.5% for electrons and 2.0% for muons, while the missing transverse momentum (MET) has a resolution of 15-25% [11].

The W signal is extracted by selecting events with one isolated lepton ($p_T^\ell > 20$ GeV and $|\eta_\ell| < 2.5$) along with significant MET due to the undetected neutrino ($\not{E}_T > 20$ GeV). These selections have a total efficiency (trigger and selection) of about 20% (40%) for the electron (muon) channel, providing a sample of about 4×10^7 (8×10^7) events for an integrated luminosity of 10 fb^{-1}. The backgrounds are at the 3% (6%) percent level. Likewise, the Z signal is required to have two opposite sign leptons ($p_T^\ell > 20$ GeV and $|\eta_\ell| < 2.5$). The efficiency of this selection is about 10% (30%) in the electron (muon) channel, yielding samples of about 2×10^6 (7×10^6) events in 10 fb^{-1} of data.

Channel	$W \to e\nu$	$W \to \mu\nu$	$Z \to ee$	$Z \to \mu\mu$
Reconstructed lepton(s)	$p_T > 20\,\mathrm{GeV}$, $|\eta| < 2.5$			
Crack region removed	$1.30 < |\eta| < 1.60$	–	$1.30 < |\eta| < 1.60$	–
Missing energy	$\not{E}_T > 20\,\mathrm{GeV}$		–	–
Events in 10 fb^{-1} [10^6]	44	80	2.1	6.7

Table I: Selection criteria for W and Z events in electron and muon channel, and resulting statistics for 10 fb^{-1} of data.

ATL-PHYS-PROC-2009-040
11 February 2009

While the invariant mass can be determined in Z boson events, the observables most sensitive to m_W are:

- The reconstructed lepton transverse momentum, p_T^ℓ.
- The reconstructed W transverse mass, $m_T^W \equiv \sqrt{2p_T^\ell p_T^\nu(1-\cos(\phi_\ell-\phi_\nu))}$.

Based on the p_T^ℓ and m_T^W distributions, m_W can be extracted by comparing the data to a set of models (template distributions) obtained by varying the value of the W boson mass parameter in the event generation. With 10 fb^{-1} of data the statistical precision is about 2 MeV for each channel, roughly matching that of the smaller but more precise Z samples.
For the above procedure to work in practice, one must predict the p_T^ℓ and m_T^W distributions as a function of the W mass. These distributions are however affected by many effects, which need to be included correctly in order to avoid biases in the mass fit. The impact of mechanisms affecting the W mass determination is estimated by producing template distributions of p_T^ℓ and m_T^W *unaware of the effect* under consideration, and fitting them to distributions *including this effect*. The resulting bias yields the corresponding systematic uncertainty.

3. Calibration and experimental uncertainties

The precise knowledge of the Z mass and width [1] allows for an accurate determination of the lepton energy scale and resolution. Given a sample of 3.9×10^4 reconstructed $Z \to ee$ events ($\mathcal{L} \sim 219$ pb^{-1}) with $85 < m_{ee} < 97$ GeV, an average mass scale (defined as $\alpha = m_Z^{\rm reco}/m_Z^{\rm truth}$) of $\alpha = 0.9958 \pm 0.0003$ was obtained on a fully simulated example sample (see Figure 1 left).
In order to correctly propagate the Z calibration measurement to the W sample, the scale needs to be measured as a function of energy. The high statistics expected at LHC allows for the refinement of doing the above calibration differentially in p_T and η (here in 8×2 bins), exploiting the energy distribution of the decay leptons, and hence measuring the linearity of the detector response.
Each event is assigned to a category (i, j), according to $p_T \times \eta$ bins (16 in total) of the two leptons (choosing $i \geq j$). For each category (i, j), the reconstructed sample is compared to the known Z lineshape, and a Z mass resolution function R_{ij} is obtained from requiring that its convolution with the theoretical lineshape matches the reconstructed distribution. The Z mass resolutions R_{ij} result from combining two lepton momentum resolutions R_i and R_j as $R_{ij} = R_i \otimes R_j$. Given N lepton bins and thus lepton resolution functions to determine, there are $N \times (N + 1)/2$ Z mass resolution functions, and thus the overconstrained system can be solved by a global χ^2 fit, allowing for a determination of the detector response for all combinations of p_T and η (see Figure 1 right).
Once the lepton scale is established, the Z transverse momentum will also serve to scale the measured hadronic recoil to the Z, which together with the measured lepton transverse momentum defines the missing transverse energy. Finally, "tag and probe" methods [12] will allow to determine the lepton reconstruction efficiency.
Backgrounds are small and mostly from well known similar heavy boson decays yielding true leptons (estimated from simulation), or from dijet events (estimated using two independent discriminators) faking leptons.

4. Theoretical uncertainties

Most QCD mechanisms affecting W distributions carry significant uncertainty, but affect W and Z events in a similar way. This is the case for non-perturbative contributions, but also for parton density (PDF) effects. At the LHC, the W and the Z are essentially sensitive to high-Q^2 sea partons, and a variation of these parameters will affect the W and Z distributions (in particular y_W and y_Z) in a highly correlated way. Since the usage of the Z for calibration effectively makes the analysis a measurement of the W to Z mass ratio, the impact of correlated effects is strongly constrained. Evaluation was based on variation of parameters.
The W width uncertainty was assumed to diminish at the LHC. The impact of QED radiation was evaluated by varying the order of the QED calculation by PHOTOS and considering general LEP precision. For details, see [14].

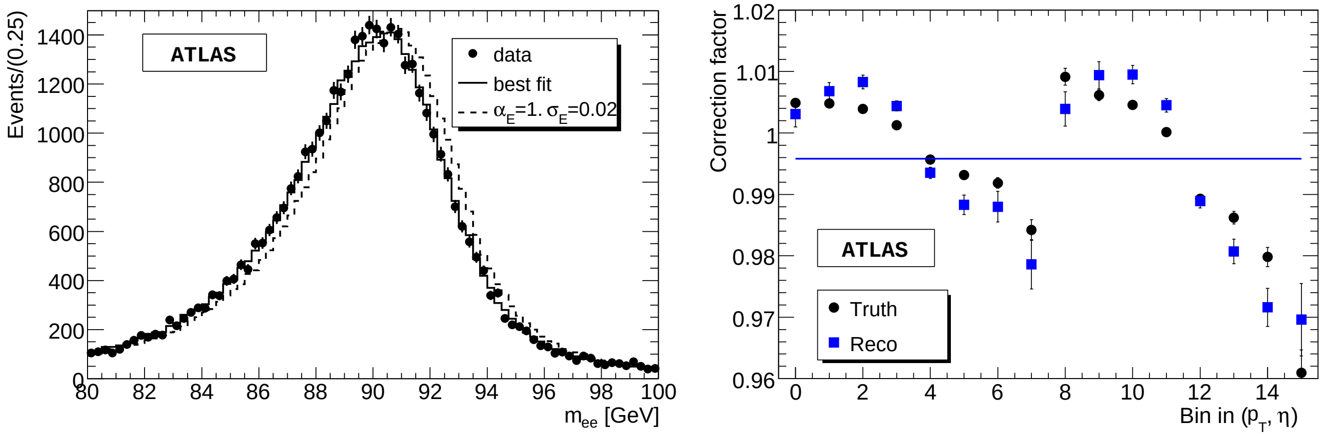

Figure 1: **Left:** Average calibration using 3.9×10^4 $Z \rightarrow ee$ events. **Right:** Differential (linearity) calibration as a function of p_T (8 bins) and η (2 bins) with same data. The two calibrations agree with each other and the generated value.

5. Results and Conclusion

The systematic uncertainties are summarized in Table II for 10 fb^{-1} of data. Assuming expected detector performance and required theoretical tools to be available, the result is a precision on m_W of 7 MeV per channel. Additional calibration processes and combining independent measurements may be required to assure precision.

Experimental effect	$\sigma(m_W)$ (p_T^ℓ)	$\sigma(m_W)$ (m_T^W)	Theoretical effect	$\sigma(m_W)$ (p_T^ℓ)	$\sigma(m_W)$ (m_T^W)
Lepton scale, lin. & res.	4	4	W width	0.5	1.3
Lepton efficiency	4.5 (e), < 1 (μ)	4.5 (e), < 1 (μ)	y_W distribution	1	1
Recoil scale, lin. & res.	–	5	p_T^W distribution	3	1
Bkg. (heavy bosons)	2	1.5	QED radiation	<1	<1
Bkg. (dijets)	0.5	0.4			
			Total	$\sim$7 (e); 6 (μ)	$\sim$8 (e); 7 (μ)

Table II: Breakdown of systematic uncertainties for p_T^ℓ and m_T^W fits in e and μ channel to m_W. All number are in MeV.

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